

6. APPLICATION OF INNOVATIVE MATERIALS

A. Advanced Materials for Friction Brakes

Principal Investigator: P. J. Blau

Oak Ridge National Laboratory

P.O. Box 2008, Oak Ridge, TN 37831-6063

(865) 574-5377; fax: (865) 574-6918; e-mail: blaupj@ornl.gov

Technology Development Area Specialist: Sidney Diamond

(202) 586-8032; fax: (202) 586-1600; e-mail: sid.diamond@ee.doe.gov

Field Technical Manager: Philip S. Sklad

(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

Contractor: Oak Ridge National Laboratory

Contract No.: DE-AC05-00OR22725

Objectives

- Identify, test, and analyze the friction and wear characteristics of advanced materials and surface treatments that enable weight reduction in truck brake components while equaling or bettering their performance. Materials of interest include intermetallic alloys, ceramic composites, titanium alloys, and novel surface treatments.

Approach

- Design and build a subscale brake material testing apparatus to investigate the friction and frictional heating characteristics of advanced materials at speeds and contact pressures similar to those in full-sized brakes.
- Investigate the nature of changes to the surfaces of materials that occur as a result of frictional contact under high energy input conditions—especially the formation of friction-induced films.
- Evaluate friction and thermal characteristics of candidate lightweight materials for heavy vehicle brakes. These include titanium alloys and ceramic matrix composites.
- Examine the characteristics of brake material wear particles, an environmental consequence of braking.
- Understand and model frictional energy dissipation and apply that knowledge to the evaluation of advanced brake materials.

Accomplishments

- Selected and tested a variety of metals, ceramics, and composite materials with the potential to serve as lightweight brake components. Down-selected two material systems, titanium-based materials and ceramic composite materials, for further study during the coming year.
- Worked with a visiting university faculty member to understand and model frictional heat partition.
- Evaluated the effects of wear testing methodology on the relative wear rankings of a series of commercial brake lining materials. Identified the role of entrapped wear particles in affecting these rankings.
- Compared the frictional characteristics of two titanium-based disc materials with those of two ceramic composite disc materials using several candidate lining materials. Compared results with traditional cast iron combinations.

Future Direction

- Evaluate currently available commercial coatings and explore new coating technologies for use on titanium alloys for lightweight brake rotor materials.
- Understand the role of particle loading on friction performance and thermal transport in candidate titanium-based composites.
- Identify lining materials that are frictionally compatible with advanced disc materials.

Introduction

Advanced aerodynamic designs and tires with lower rolling resistance can improve fuel efficiency of trucks. However, as these approaches decrease the drag forces on trucks, the demands on truck braking systems increase. Brake engineering involves design, instrumentation and controls, and materials development. This project specifically addresses the latter. Brake materials must exhibit a balance of properties, including frictional stability over a wide temperature range, appropriate thermal properties, dimensional stability, corrosion resistance to road deicers, and wear resistance. From a practical standpoint, they must also be cost-competitive. Opportunities exist to employ advanced materials to create lighter-weight braking systems that will enable new technologies to raise the fuel efficiency of a vehicle without compromising its safety and reliability.

This project addresses the science and engineering of advanced structural materials and surface treatments that show potential as truck brake friction materials. Testing of such new materials is made more cost-effective by using small specimens to screen the most promising candidates. To this end, a subscale brake tester (SSBT) was designed and built. It was instrumented to measure normal force, friction force, surface temperature, and vibrations during braking. An attachable water spray system enables study of the effects of wet and dry braking. The SSBT has been a workhorse in recent studies involving a variety of both traditional and nontraditional brake materials. Analysis of SSBT results is supplemented by optical microscopy, electron microscopy, and transmission electron microscopy of friction-induced films.

eliminated those with low softening points, brittle behavior, corrosion sensitivity, and environmentally unacceptable wear byproducts. A list of the materials evaluated, along with comments on their advantages and disadvantages, was presented in the FY 2003 Annual Progress Report. Table 1 provides a summary of the materials tested to date. Most of the disc materials, particularly the composites, are not mass produced; therefore, special samples were

Table 1. Candidate friction material combinations

Disc specimen material	Mating material(s)
Traditional gray cast iron	Jurid 539 disc brake lining Performance friction carbon-metallic pad (type 10) Armada AR2, AR4, AR5 drum brake lining materials
SiC particle-reinforced aluminum alloy (Al-MMC)	Specially formulated lining for Al-MMC (Plymouth Prowler)
Fe ₃ Al intermetallic alloy	Jurid 539 disc brake lining
Ceramic composite (C/SiC)—GE Power Systems, LLC	Jurid 539 disc brake lining Same material as the disc
Ceramic composite (SiC/Si)—Redundant Materials	Same material as the disc
Ceramic composite (C/SiC)—Starfire Systems	Carbon felt composite Copper-carbon composite
Titanium alloys (Ti-6Al-4V, and Ti-6Al-2Sn-4Zr-2Mo)—TIMET	Jurid 539 disc brake lining
Titanium matrix composite (TiC)—CermeTi C-10, Dynamet Tech	Performance friction carbon-metallic pad (type 10)
Thermally-sprayed titanium—Red Devil Brakes	Metallic and semimetallic pads materials supplied by Red Devil Brakes

Selection of Candidate Materials

Studies of the structure, composition, and physical properties of candidate materials have

purchased specifically for our tests. The sliding partners (linings) for the disc materials were selected based on factors such as comparison with similar linings tested against cast iron, recommendations from suppliers, and materials having thermo-physical properties that made them likely partners for given disc materials.

After evaluating the materials in Table 1 from an overall performance and cost standpoint, we decided to limit our studies to (1) titanium-based alloys, including composites and coated alloys, and (2) ceramic composites that had shown encouraging results both in our work and in limited vehicle braking tests.

During FY 2004, dozens of experiments were conducted to characterize the effects of speed and contact pressure on the friction coefficient and frictional temperature rise for both titanium-based and ceramic composite disc materials. Results are summarized in the following sections. Polished cross sections of the materials were examined to document their structure, and thermal property measurements were made for use in modeling.

Titanium-Based Disc Materials

Titanium-based materials offer higher temperature resistance and better corrosion resistance than aluminum-based composites, but they are not widely used in brakes. In fact, the current applications for titanium lie mainly in automotive racing (Red Devil Brakes Co., Mt. Pleasant, Pennsylvania). Disc friction surfaces of the titanium alloys are thermal-spray-coated. Such materials were included in our investigation using fully metallic pad materials supplied by Red Devil Brakes.

It was also of interest to determine whether noncoated titanium alloys could be used for brake discs. Therefore, we purchased titanium-based composite material discs from Dynamet (Burlington, Massachusetts) whose CermeTi materials contain hard particles in a titanium alloy matrix.

Figures 1 and 2 summarize friction data on the effects of sliding speed and contact pressure on the friction of titanium-based disc materials against several pad materials. Figures 1 and 2, respectively, show data for 150 N and 300 N applied force. Data for Jurid 539 against gray cast iron (GCI) are also plotted for comparison.

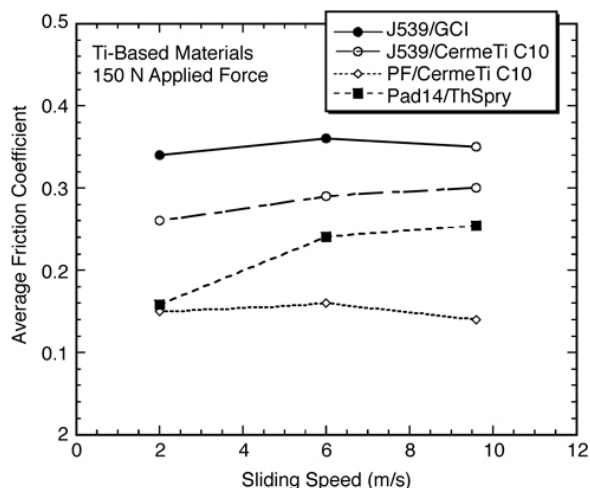


Figure 1. Effect of sliding speed on the friction of several titanium-based disc materials (low applied force).

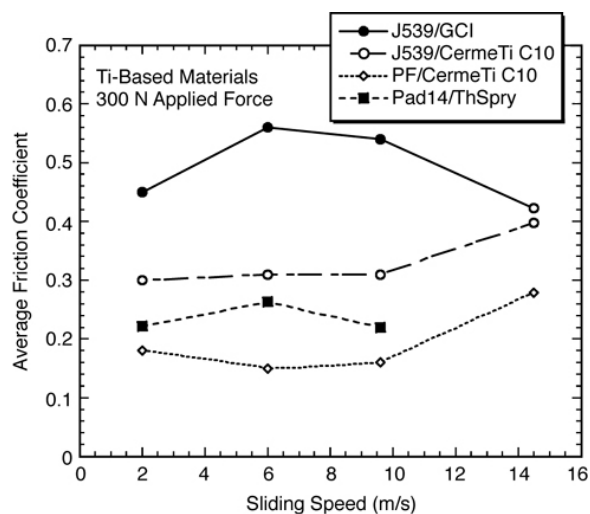


Figure 2. Effect of sliding speed on the friction of several titanium-based disc materials (high applied force).

Friction coefficients for the various combinations spanned a relatively wide range, depending on applied conditions. Other things being equal, the lower the friction coefficient, the more applied force is required to produce the same stopping distance.

At both levels of applied force, the highest friction coefficients were obtained from Jurid 539 sliding on GCI; those for the other material combinations, involving titanium-based discs, tended to be about $\frac{1}{2}$ to $\frac{3}{4}$ as high. However, these results must be viewed with the understanding that our tests do not simulate every aspect of actual truck

braking characteristics. Transfer films seemed to be more difficult to create on the nonferrous materials and took place over a period of time. To precondition the surfaces before taking data, we began with coarsely abraded surfaces and ran a series of conditioning stops. Surface engineering may be required to facilitate transfer film formation, and that subject remains for further investigation.

In general, to obtain the higher levels of friction typical of commercial materials sliding on cast iron, it was necessary that the disc materials be frictionally heated until they became very hot. This temperature characteristic is both an advantage and a disadvantage. The advantage is that titanium-based materials seem less prone to 'fade' (loss of braking at high temperature) and in fact probably behave better at high temperature. The disadvantage is that the titanium brakes tend to run hotter than cast iron brakes, and thermal management would need to be applied in order to use them effectively. Use of vented rotors or other designs to induce forced cooling in the wheel well are other options for addressing that issue.

Ceramic Composite Disc Materials

Ceramic composite materials (CCMs) have been of interest for high-energy braking applications such as high-speed trains, race cars, and high-performance sports cars. Their low density offers the potential for significant weight savings; their high hardness suggests wear resistance; and their high-temperature resistance is attractive. However, the costs and special procedures associated with processing, handling, and finishing CCMs have been significant impediments to their widespread use. CCMs were included in this project to assess any relative performance benefits over titanium materials or conventional materials. Furthermore, there have been limited field trials of lightweight CCM brakes that showed up to 8% fuel economy savings on a GM sports utility vehicle.

Carbon/SiC ceramics were previously tested under a joint project with GE Power Systems. Now we are working with two other CCM suppliers: Starfire Systems (Malta, New York) and Redundant Materials, Inc. (Clarence Center, New York). Test discs were purchased from both of these companies. Previous experience from the GE carbon composites program indicated that good results could be obtained from self-mated sliding

combinations. In addition, two candidate lining materials were provided by Starfire Systems (a carbon-felt composite and a carbon-copper composite). Using the same testing protocols as for the titanium-based materials, a series of friction tests were performed on CCM combinations. Results are summarized in Figures 3 and 4.

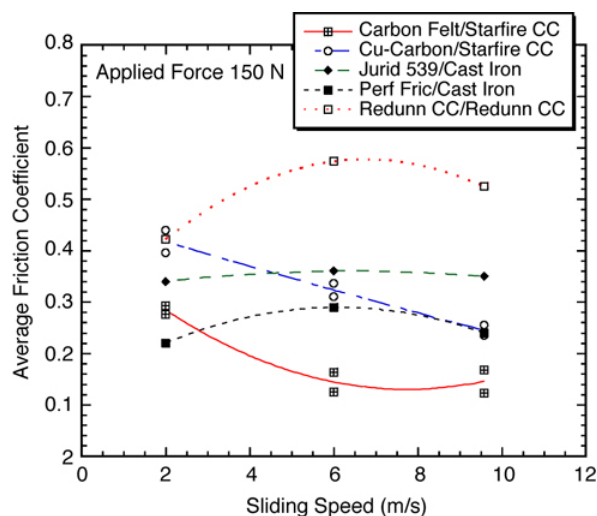


Figure 3. Effect of sliding speed on the friction of various CCM disc/lining material combinations at 150 N force.

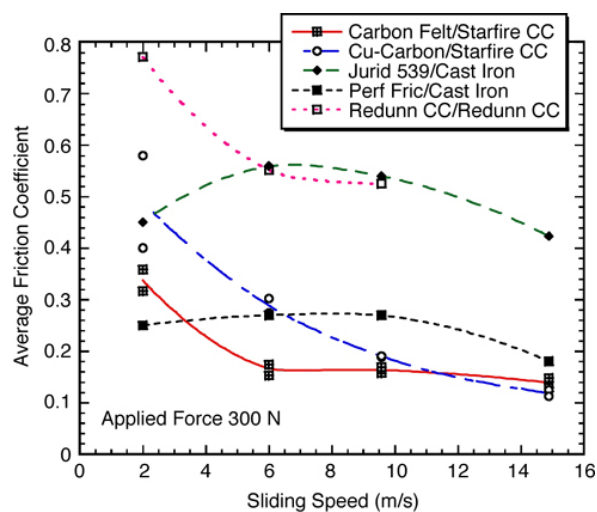


Figure 4. Effect of sliding speed on the friction of various CCM disc/lining material combinations at 300 N force.

Several trends are evident from the data in Figures 3 and 4. The friction coefficients of the CCMs tend to decrease as the sliding speed increases. This is somewhat unexpected, because for

carbon-based brakes, like those used in racing and aircraft brakes, friction tends to increase with severity of use (repeated braking or high-pressure application that increases the brake temperature). Second, the copper-carbon lining material against the Starfire Systems materials produced better results than the carbon felt. Recent discussions with Starfire engineers suggest that further improvements are possible using a new pad formulation against their CCM, and ORNL is in the process of obtaining this material for further testing.

The SiC/silicon material prepared by Redundant Materials had the highest friction coefficients at both low and high pressure, but it suffered from brittleness resulting from the layers of silicon within the composite.

Temperature Modeling

While this report has primarily addressed results from friction measurements, considerable data on temperature rises were also obtained for analysis. One measure of the efficiency by which the energy of braking is converted into heat is the thermal conversion parameter (Q_f) defined here as follows:

$$Q_f = c(\Delta T/Fx)$$

where ΔT is the temperature rise of the disc specimen surface during a constant speed drag, F is the average measured friction force, and x is the distance slid during the drag. The constant c is a function of the testing geometry and the fact that only the heating of the disc is considered, not the heating of the pad as well. Q_f can be thought of as the efficiency of a given rotor material to convert frictional work (Fx) into a certain surface temperature rise (ΔT). The higher Q_f , the more readily the frictional work of braking translates into the heating of the disc surface. Table 2 lists experimentally obtained values for several of the material combinations. For example, for our particular testing configuration, Jurid 539 against CermeTi discs results in $(5.9/1.1 =) 5.36$ times more temperature rise per unit of frictional work than Jurid against GCI.

Table 2. Thermal conversion parameter (Q_f) for various material combinations (300 N test results)

Disc material	Sliding partner	Q_f (°C/N-m)
GCI	Jurid 539	1.1×10^{-3}
GCI	Perf. friction	1.5×10^{-3}
CermeTi C10	Jurid 539	5.9×10^{-3}
CermeTi C10	Perf. friction	6.7×10^{-3}
Red Devil Ti	Pad type 14	15.4×10^{-3}
Starfire CCM	Carbon felt	17.6×10^{-3}
Starfire CCM	Copper carbon	12.4×10^{-3}
Redundant CCM	Redundant CCM	2.70×10^{-3}

During the summer of 2004, ORNL was joined by Timothy Ovaert, University of Notre Dame. He analyzed several current models for heat partition in braking and developed a new model that allows estimation of the partitioning of heat between the slider (pad) and rotor. His model will be used during FY 2005 to help understand the implications of relative heat transfer characteristics when optimizing material combinations for brakes.

Conclusions

Studies have been conducted of a variety of candidate lightweight truck brake materials. Of these, titanium alloys offer a number of attractive characteristics, but their low thermal conductivity and wear behavior must be considered as well. The use of surface coatings or treatments is expected to enable the materials to perform quite well as brakes. Further work in FY 2004 is planned to better understand the friction and wear behavior of titanium alloys and to evaluate several alternative coating methods for rotor surfaces.

Publications

M. Mosleh, P. J. Blau, and D. Dumitrescu, "Characteristics and Morphology of Wear Particles from Laboratory Testing of Disk Brake Materials," *Wear* **256**, 1128–34 (2004).

J. Qu, P. J. Blau, T. R. Watkins, O. B. Cavin, and N. S. Kulkarni, "Friction and Wear of Titanium Alloys Sliding against Metal, Ceramic, and Polymer Counterfaces," *Tribology International*, accepted for publication (2004).

B. Advanced Composite Structural Cab Components

Principal Investigator: Michael A. Wieck

Delphi Automotive Systems

Delphi Steering Division

3900 Holland Road, MDC-2

Saginaw, MI 48601-9494

(989) 757- 4283; fax:(989) 757-4295; e-mail: michael.a.wieck@delphi.com

Technology Development Area Specialist: Sidney Diamond

(202) 586-8032; fax: (202) 586-1600; e-mail: sid.diamond@ee.doe.gov

Field Technical Manager: Philip S. Sklad

(865) 574-5069; fax:(865) 576-4963; e-mail: skladps@ornl.gov

Contractor: Delphi Corporation

Contract No.: 4000009401

Objectives

- Develop an advanced composite cab structural component for a Class 8 tractor:
 - Develop the design, materials, and manufacturing process for using continuous-oriented, fiber-reinforced composites for affordable commercialization within 5 years of beginning the project.
 - Reduce the existing mass by at least 30% from 22.8 to 15.96 kg.
 - Meet or exceed the performance of existing materials.
 - Meet customer target cost.

Approach

- Organize a value analysis/value engineering (VAVE) workshop to generate different options for design and manufacturing.
- Develop finite element analysis (FEA) to develop and optimize design options.
- Perform a process cycle study, make necessary panels, and study Class B surfaces.
- Conduct design failure modes effects and analysis (DFMEA).
- Construct prototype parts and verify the proposed design using a design validation (DV) test.
- Release final designs, construct production tools, perform process failure mode and effects analysis (PFMEA), and undergo process validation (PV) of the production phase.
- Commercialize and start production.

Accomplishments

- During the first half of the fiscal year, completed a proof-of-process study with generic block mold, which demonstrates the feasibility of infusing thin-walled laminates. Then completed a pre-PV study with production foam core and prototype composite mold for areas 3 and 4 of the lower B-pillar.
- Completed DV testing of prototype components in full cab build. (Door slam test had gone through three life cycles and sustained no structural issues) Completed fastener torque studies in molded sample blocks.

- Updated the system DFMEA with suppliers and customer.
- Refined FEA models to include material properties from actual material test data, developed local composite reinforcements to improve stiffness, and studied the effect of processing tolerances for an affordable product.
- Simplified construction in the air duct area by making the air duct a separate, post-mold fastened part.
- Reduced metal usage by eliminating large steel plate and using more localized attachments with composite reinforcements.
- Produced assembly drawings, CAD models, some design details, and specifications for quote packages.
- Selected a production source for final assembly.
- Reduced flange areas to 3 mm in thickness.
- Performed cure-cycle study, made composite panels, conducted Class B surface activities.
- Made plaques and part skins using a conductive gel coat to demonstrate elimination of post-mold spray conductive primer. Validated conductive gel coat to replace post-mold spray primer system (cost savings).
- Finalized metal hardware material specifications.
- Determined optimal machining process parameters (tool shapes, feeds, and speeds for drill/tap of composite laminate over metal hardware).
- Created 2-dimensional (2D) lay-flat fabric patterns from 3D part geometry with slits and darts to minimize fabric shear and to optimize the overall fabric blank size.
- Completed environmental testing.
- Finished final design math model and process.

Future Direction

- Conduct PFMEA with sourced supplier and customer.
- Finalize specifications, assembly, and detail drawings.
- Release final design, release remaining production tools, and validate the production phase.
- Begin production.

Introduction

Significant strides forward were made in FY 2004 on the Advanced Composite Cab Structures project. Within Delphi, the project moved from a development activity to an implementation team; and with the progress outlined in this report, both cost and mass targets were achieved.

To accomplish the project objectives, the Delphi-led team replaced the present production liquid-compression-molded two-component post-bonded assembly made of non-oriented chopped fiberglass with a single resin-transfer-molding (RTM) processed foam core structure enclosed with a thin laminate of oriented and continuous-length fiberglass.

Design and Process Failure Modes and Effects Analysis

A system-based DFMEA was initiated at the Delphi facility in early 2003 and was periodically updated as the production intent design was refined. It included a review at Delphi's original equipment manufacturer (OEM) partner's assembly plant with representation from engineering, quality, and purchasing. Another DFMEA was held in June 2004 with the OEM engineers after the DV tests were completed. The suppliers of individual components and final molder have responsibility for performing PFMEA and creating process control plans after final sourcing. Delphi participates in each FMEA.

Pre-PV Development: Resin Cure Times and Thin-Walled Infused Laminates

To determine the proper tooling and cure cycle, Delphi and Reichhold, a leading resin supplier, conducted multiple cure-cycle studies at Delphi's Composite Lab in Salt Lake City. The goal was to make a resin recipe that would meet a requirement for a 22-min full-cure cycle at 120°F. Initial studies completed in February 2004 indicated that a processing temperature of 120°F for the cure cycle was possible.

One of the major design obstacles of this project was the processing of thin (1.0–1.5 mm) laminates with RTM. Some of the concerns originated around tolerances and geometric stack-ups of all the components within the molded assembly. Secondary concerns included the response of the foam core, tooling, and hardware during infusion. Multiple layers of fabric and reinforcement were located between various foam cores.

To expedite pre-PV development, we selected a small section of the molded assembly, rather than work with the complete assembly. Pre-PV development used results from early proof-of-concept development.

Proof-of-concept development used a rectangular box (4×6×16 in.), a cross section of which is shown in Figure 1. This shape closely represents one of the longest infusion sections of the actual component. The tool was designed to infuse the 16-in. length, with an injection and a vacuum port on opposite ends. The cover of the tool was made of clear glass to allow visual inspection and videotaping of the resin flow front.

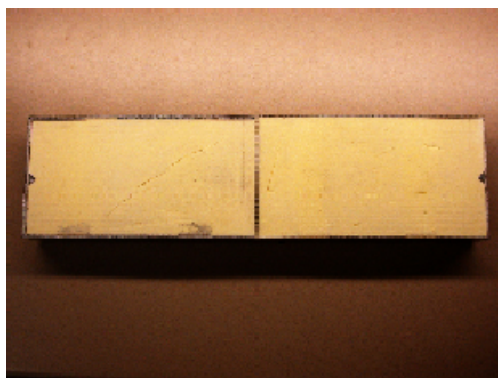


Figure 1. Proof-of-process mold block.

Almost 50 individual infusion runs were conducted with very positive end results. In the course of the proof-of-concept study, it was determined that laminate thicknesses of less than 1.5 mm were achievable. The limiting factors in achieving thin laminates were the tolerances of the tooling and the foam cores; but even on areas where the fabric was pinched because of irregularities or multiple plies, it was still possible to infuse. To maintain regular laminate thicknesses between the top and bottom surfaces, because of pressure gradients, special geometries were added to the foam cores. With respect to internal supports and multiple plies, the development showed a process that was able to fully infuse any of the combinations we were able to create. A close-up view of a proof-of-process through-part reinforcement is shown in Figure 2.



Figure 2. Close-up view of proof-of-process composite block with reinforcement.

Other findings from process development were that pressure/vacuum values as well as the foam density were optimized. With a low-density foam core, vacuum assist, and low resin pressure, consistent processing results were obtained with few air voids and an infusion time of 1 minute. High pressure resulted in foam compression, allowing more resin into the part, and did not shorten the injection time. Finally, a modified resin with less inhibitor was used to allow the cure cycle (from mixing to cured part) to meet an acceptable cycle time (<22 minutes) at a heated tool temperature of <120°F.

The next step in developing the pre-PV molding process was to build a larger tool with the actual part geometry (foam core areas 3 and 4) to ensure pre-PV process capability. Two production-level foam core tools were made to allow refinement of the process

on an actual production geometry tool. Figure 3 shows a view of an open aluminum-based RTM pre-PV tool. Figure 4 shows the first part made out of an aluminum-based pre-PV tool, and Figure 5 shows a cutout portion of a molded part section view from the aluminum pre-PV tool. The part was made using production-intent resin with a low inhibitor level and production-intent foam. The resulting composite part was very close to the targeted weight.



Figure 3. Open view of aluminum-based RTM pre-PV tool for sections 3 and 4.



Figure 4. First pre-PV part made out of aluminum-based RTM tool.

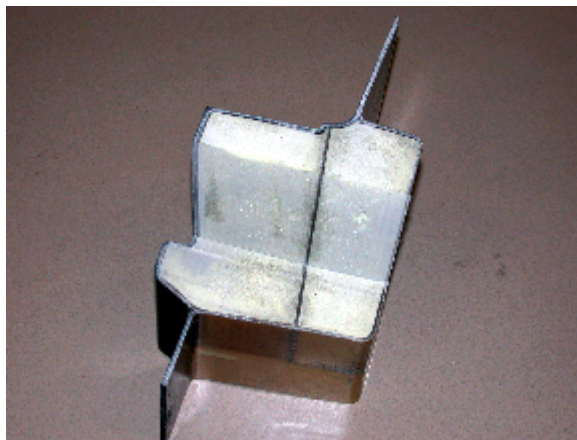


Figure 5. A cutout portion of molded pre-PV part from aluminum tool.

Hardware: Secondary Machining Operations

A key design element to minimize cost was insert molding of the metal fasteners into the foam cores. Another cost-saving method was to ensure that drilling and tapping time were optimized. To ensure optimal drill and tap cycle time after parts were made, a study was conducted. Figure 6 shows a robotic machine cell that was used to optimize the drilling method. Various drill bits and speeds were determined to help remove chips, and countersink methods were developed to avoid composite damage during tapping.

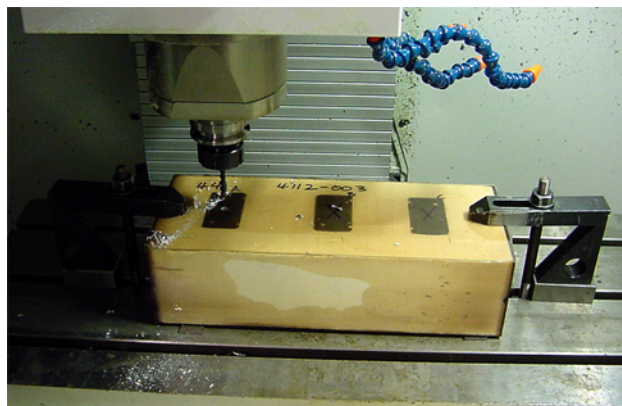


Figure 6. Drill and tap time study fixture for hardware molded test block.

Analytical Work—FEA and Fabric Pattern Development

The production design direction has been finalized, and FEA and CAD data files are undergoing final updates before production release. FEA indicates that all performance requirements will meet or exceed requirements.

Fifteen individual fabric pieces are required in the molding operation. The initial lay-flat patterns developed did not drape well over the foam cores or into the molding tool. Alternative lay-flat software is being investigated.

Cost Reduction: Conductive Gel Coat

A systematic review of the final assembly cost indicated that masking, conductive spray primer, and finish were areas with great cost reduction potential. By implementing a conductive gel coating in the composite molding, preliminary estimates showed that finished assembly cost could be reduced by up to 10%. Delphi identified a conductive gel coat system that had already been approved by the OEM partner in other applications and fabricated flat panels representative of exterior part surfaces (see Figure 7) with this conductive gel coat. These samples were forwarded to the OEM partner for oven and environmental conditioning. Following this conditioning, surface finish and resistivity will be evaluated.

Testing Activities

Fastener testing. Tests for torque and pullout load had been conducted on several M5 and M6 threaded fastener designs in composite panels with steel plates. Other sizes were also tested according to their application category [e.g., Federal Motor Vehicle Safety Standard (FMVSS), heavy load bearing, interior to the door seal, exterior to the door seal].

The foam block with hardware after drilling and tapping can be seen in Figure 8. To ensure that new hardware will work, a study of hardware bonding and corrosion resistance were conducted.

Torque and pullout load between composite and metal hardware embedded in foam was determined using various surface preparations for metal hardware. The torque fixture used for the study is shown in Figure 9. The purpose was to determine

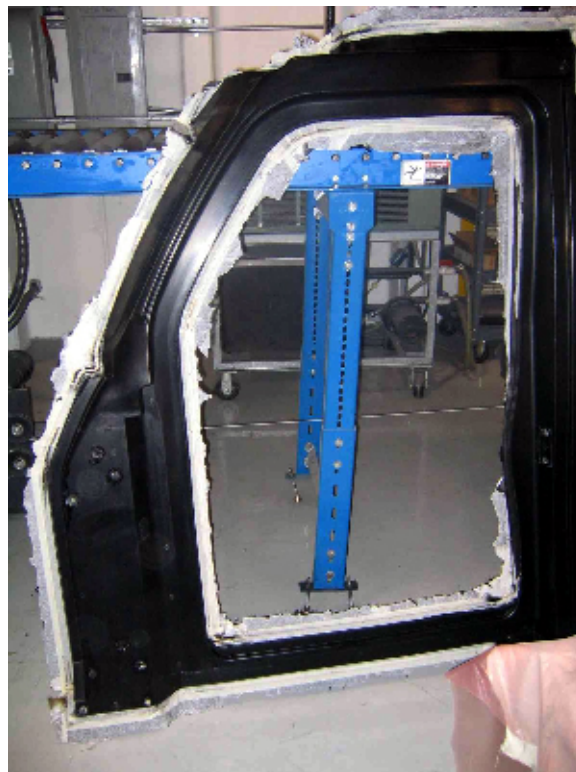


Figure 7. Exterior surface showing conductive gel-coat.



Figure 8. Hardware molded block after drilling and tapping.

that threaded fasteners meet FMVSS requirements. The results showed that all various surface preparations were acceptable for bonding with the proposed composite materials.

Expansion testing. Blocks of the same composition of composite and foam design have been heated to process temperatures of 225°F for

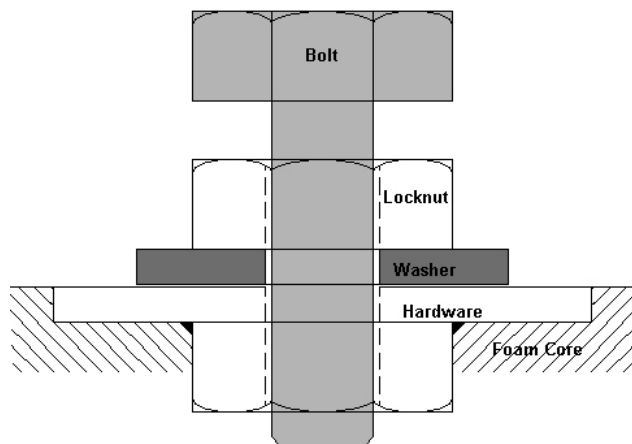


Figure 9. Torque test fixture for hardware molded test block.

one hour with no effects on the part due to variations in expansion rate among the differing materials.

Environmental testing. Environmental testing was conducted on both composite test blocks and cut-away sections of prototype parts (Figure 10). The effect on the foam, the hardware, and the laminate was determined. The results, as expected, verified that the foam and composite laminate construction protect the hardware from the environment and resist moisture penetration into the structure.



Figure 10. Hardware molded block after corrosion.

To meet the corrosion requirement, it was decided, with customer approval, to use stainless steel for machined and tapped holes outside the seal and carbon steel material in areas inside the seal. The corrosion resistance test was performed according to the OEM's standard practice on drilled metal fasteners. The results showed that Dupont's E-coated steel exhibited similar result as current production parts. Since the cost difference was minimal, the team decided to use E-coat to keep with the customer specifications.

Summary

These are the highlights for the progress during FY 2004.

1. Reduced laminate thickness from 3.0 to 1.5 mm using 30% fiber volume with production-intent resin and process. The visual inspection looked good. Performed mechanical testing of the panels and used the test properties to refine the FEA model of the cab structure.
2. Reduced component mass by 32% over current composite technology.
3. In-molded hardware to meet process requirements.
4. Proved 1.5-mm-thick molding process with area 3 and 4 pre-PV tools using foams from production-intent 3 and 4 foam tools.
5. Used in-mold conductive gel coating to reduce process steps and material cost of conductive spray primer.
6. Successfully completed cab shake testing of the cab structure using VARTM thin-walled laminates over foam cores with embedded metal hardware. This same cab structure completed the final stages of DV testing, again with no failures. Torsion and pullout testing also have met specifications.
7. Met all mass, performance, and cost objectives.

C. Advanced Composite Structural Chassis Components

Principal Investigator: David E. Witucki, PE

Delphi Corporation—Saginaw Steering Systems Division

3900 Holland Ave., Saginaw, MI, 48601

(989) 757-4984; fax: (989) 757-4295; e-mail: david.witucki@delphi.com

Technology Development Area Specialist: Sidney Diamond

(202) 586-8032; fax: (202) 586-1600; e-mail: sid.diamond@ee.doe.gov

Field Technical Manager: Philip S. Sklad

(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

Contractor: Oak Ridge National Laboratory

Contract No.: DE-AC05-00OR22725

Objectives

- Develop an economical, long-fiber-reinforced manufacturing procedure using continuous and/or oriented chopped fibers for structural chassis components for Class 7&8 trucks.
- Reduce the mass of these components by 60%.
- Commercialize and annually produce these components, reducing vehicle mass by about 50 kg/vehicle and significantly increasing North American carbon fiber demand annually, within 5 years of project commencement.

Approach

- Conduct value analysis/value engineering workshop(s) to conduct function analysis and brainstorm composite solutions to each component function.
- Develop finite element analysis (FEA) models on both the component and system level. Conduct structural optimization (topology and shape/sizing) of components for “material-efficient” designs.
- Build and test prototypes.
- Secure production orders for the components developed within the scope of the project.

Accomplishments

- Received production purchase orders from two customers for four different models of composite tie rod tubes to be supplied by Delphi. Current total volume is approximately 6000 units per year. Samples have been supplied to three additional customers.
- Presented the paper “Composite Tie Rods for HD Truck Applications” at the Society of Plastics Engineers (SPE), Automotive Composite Conference. In addition, this product was nominated for SPE’s Plastics Innovation award and has been named a finalist in the run for the award in the Chassis category.
- Completed initial durability and stiffness testing on a “proof-of-concept” composite-reinforced, thin-wall steel tube main support.
- Used composites research/design concepts to develop and commercialize an aluminum z-beam that resulted in over 27 kg mass savings per system.
- Achieved 32 kg of the 50 kg target for system mass reduction with the combined mass savings of the composite tie rod tube and aluminum z-beam.

Future Direction

- Continue investigation into lower-cost tie rod tube designs and processes.
- Validate composite tie rod tube for higher-volume, front steer applications.
- Investigate follow-up project for main support development with second tier-one chassis system supplier.

Introduction

In response to a request for proposals from UT-Battelle/Oak Ridge National Laboratory (ORNL) in February 2001, a submission from Delphi Corporation led to the award of a subcontract for the development of advanced composite structural chassis components with the objectives listed earlier.

Sponsored by DOE, the duration of the subcontract is 3 years with an estimated cost of \$2.5 million. This project is a 50/50 cost share between ORNL and industry. In this project, Delphi Corporation, the world's largest automotive Tier 1 supplier, partnered with an industry leading Tier 1 supplier to the truck and trailer industry and focused on three components in a chassis/suspension system: lateral links, main supports, and z-beams.

Composite Tie Rod Tube Status

Through the third quarter of 2004, more than 6000 carbon-fiber-reinforced tie rod tubes have been installed on passive-steer, auxiliary lift axle systems. Delphi has secured production orders for tubes of four lengths for two customers. Samples have been supplied to three additional customers.

This tube was nominated for the SPE Automotive Division Innovation Award in the Chassis Category and was selected by SPE's board of directors as a finalist. A formal presentation will be made to a blue ribbon panel composed of technical trade publication and industry experts for final evaluation. For more information on the SPE and the award program, visit <http://www.speautomotive.com/inno.html>.

Production tooling has been released for a lower-cost tube assembly, and production-intent samples are currently undergoing validation testing for both auxiliary lift axles and front steer applications. Test results have been mixed so far; durability testing has been favorable, but buckling capacity has degraded with the new design. Additional samples are being fabricated with alternative lay-up and materials, and preliminary

results have been encouraging. Unfortunately, these design changes are beginning to erode the original forecast of 20% cost savings for this design.

Z-Beam Status

Delphi's Tier 1 partner has introduced a cast aluminum z-beam based on FEA topology optimization completed for a composite design. Figure 1 illustrates both a preliminary composite concept and the similar final production aluminum design. The cast aluminum solution reduced the mass by approximately 7 kg and was at cost parity or below current welded steel designs. Since four z-beams are used in each system, 28 kg of total system mass was eliminated.

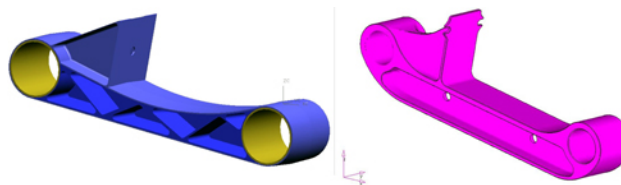


Figure 1. Composite z-beam concept (left) and current production cast aluminum beam.

Main Support Status

Testing has been completed on the first proof-of-concept main support. This assembly consisted of a relatively thin-wall steel tube, welded-in end fittings, and epoxy/carbon fiber composite reinforcement. The test sample completed the side load test schedule but failed approximately two-thirds of the way through the brake load schedule. The failure occurred in the welded joint between the inner steel tube and the end fitting (see Figure 2). It is anticipated that this can be overcome with a slight redesign to the interface of the metal parts and the addition of composite reinforcement around the end fitting.



Figure 2. Proof-of-concept main support after side and brake load testing.

Vertical stiffness measurements were taken of the baseline, current production steel main support, thin-walled steel tube, and final composite-reinforced tube. Stiffness data are shown in Figure 3. The composite-reinforced axle beam very closely matched the stiffness of the baseline steel beam, validating the previous FEA and structural optimization efforts.

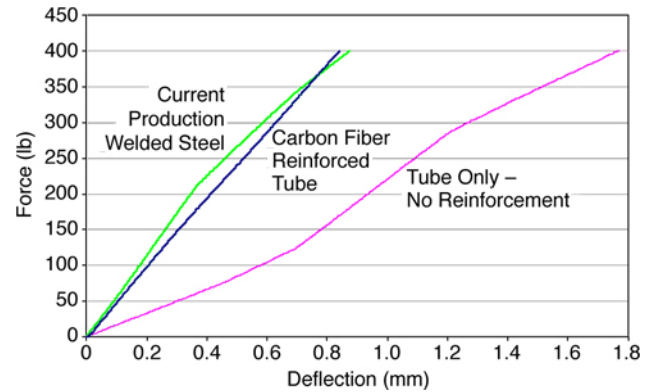


Figure 3. Main support stiffness testing.

The prototype proof-of-concept samples were 26.3% lighter (20.9k kg or 46 lb) than the baseline and employed 5.9 kg (13 lb) of dry carbon fiber fabric. Further mass reduction is anticipated because the tubing selection for fabrication of the prototype was based on availability. The fully optimized design calls for thinner steel tubing.

D. Carbon Fiber SMC for Class 8 Vehicle Hoods

Principal Investigator: Nicholas A. Rini

Volvo Trucks North America, Inc.

P.O. Box 26115, Greensboro, NC 27402-6115

(366) 393-2771; fax: (336) 393-2773; e-mail: nicholas.rini@consultant.volvo.com

Cliff Eberle, Project Manager

(865) 574-0302; fax: (865) 574-8257; e-mail: eberlecc@ornl.gov

Technology Development Area Specialist: Sidney Diamond

(202) 586-8032; fax: (202) 586-1600; e-mail: sid.diamond@ee.doe.gov

Field Technical Manager: Philip S. Sklad

(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

Contractor: Volvo Trucks North America

Contract No.: 4000010928

Objective

- Develop carbon-fiber (CF) sheet molding compounds (SMCs) and processing techniques that will enable serial production of Class 8 truck hoods with structural integrity, class A surface quality, significantly reduced mass and will be competitive in cost with existing glass-fiber SMC molded components.

Approach

- Accumulate material property data to establish reliable design properties that can be utilized for engineering design analysis.
- Perform finite-element analysis of a CF SMC-based Class 8 hood design.
- Evaluate consistency and repeatability of CF SMC material properties, processing techniques, and surface quality.
- Evaluate mass savings and costs.
- Confirm predicted results by constructing prototype hoods and performing accelerated endurance tests.

Accomplishments

- Designed, built, and used a development tool in CF SMC molding trials.
- Successfully molded CF SMC materials in thicknesses ranging from 1.0 to 3.0 mm.
- Attained CF SMC material for structural applications in near final form, exhibiting good molding characteristics and using manufacturing processes very similar to those for glass-fiber SMC. Costs are reduced by approximately 50% compared with currently available commercial CF bulk molding compound materials.
- Performed initial work on CF SMC with Class A surface quality that has eliminated several proposed surface enhancement materials and processes.
- Conducted adhesive bonding prescreening trials of the CF SMC structural material that have produced data indicating lap-shear values generally two times that of comparative glass-fiber SMC.
- Completed preliminary cost and weight evaluations for the CF SMC hood.

- Completed the design, procurement, building, and installation of a CF SMC compounding line to supply materials supporting this research and development project.
- Built eight prototype hoods using existing production tools to evaluate processing characteristics of various combinations of lightweight SMC materials.

Future Direction

- Continue evaluation of CF materials and surface treatments from various suppliers.
 - Pursue cost reduction and supply stabilization of CF SMC materials.
 - Pursue low-density glass-fiber-reinforced materials and process developments to provide lightweight Class A surface quality exterior panels.
 - Use the CF SMC compounding line to produce CF materials to support ongoing development.
 - Follow up Class 8 truck hood costs and weights based on CF SMC material and process developments.
 - Evaluate CF SMC hood development status and determine if a business case can be made to pursue serial production of CF-reinforced heavy truck hoods.
-

Introduction

The mass of light automotive and commercial heavy-duty vehicles can be reduced using modern lightweight, high-performance composite materials. The reduction in vehicle mass translates into an increase in fuel efficiency. Currently, polymeric CF composites are used in low-volume, high-performance applications such as spacecraft, aircraft, and racecars. The CF-reinforced composites can reduce vehicle body mass by 40% to 60%. However, market conditions and technical barriers inhibit their use in high-volume automotive applications.

Class 7 and 8 trucks offer a lower production volume, lower technical barriers, and financial incentives that can justify a modest price premium for competent lightweight materials. The aim of this project is to accelerate the commercial implementation of high-performance, lower-cost CF SMC material body components for Class 7 and 8 trucks. As utilization of CF SMC develops and the technology matures, it is foreseeable that CF SMC will migrate into the high-volume automotive market.

The project was initiated by performing a comparative finite-element analysis of a hood configuration made of glass-fiber SMC material that had been validated through modeling, accelerated endurance tests, and field test. Based on expected CF physical and mechanical properties, hood structural and surface component material thicknesses were reduced through several iterations

to determine the effect on hood system stress states and displacements. Modal analyses were performed to determine mode shapes, and complete vehicle models were used to obtain dynamic responses in the frequency domain. Fatigue life comparisons were made based on the complete vehicle model transient analyses.

Based on the initial investigation, it was concluded that a competent hood could be produced with a 40% to 60% reduction in hood mass if a CF SMC material could be produced that would consistently provide the physical and mechanical properties targeted.

CF SMC Material Search and Comparative Testing

A search was initiated to find suppliers of polymers and CFs combined in a useable SMC. Materials from Zoltek, SGL, Toray, Grafil, and others were evaluated. Early on, two significant obstacles became evident: completely wetting out the CF and defilamentizing the fiber bundles. Work with suppliers is ongoing to optimize chemistry and processes to consistently provide CF SMC material with the targeted material properties. Short beam shear tests based on ASTM D2344/D 2344M were used to screen material samples with various combinations of resins and additives. More than 150 samples were evaluated. Materials that performed well in the short beam shear screening were used to make plaques to measure material

properties. Good progress has been made in obtaining the targeted mechanical properties, as shown in Table 1.

Table 1. Percentage of target values achieved (updated April 2004)

Percent (%) of Target Value				
Property	Tensile strength	Tensile modulus	Flexural strength	Flexural modulus
Percent achieved	86%	97%	118%	107%
Coefficient of variation	0.05	0.09	0.09	0.10

Class A Surface Quality Development

The development tool was used for Class A surface quality development trials. Parts were molded using combinations of two CF loadings, three resins, two surfacing veils, and in-mold coating. Processing parameters were set similar to those of the glass-fiber SMC components. Although some progress was made, several of the materials and processes were eliminated from further consideration. It appears that a substantial effort will be required in materials and process development to achieve CF SMC panels with Class A surface quality. Because of the anticipated higher cycle times and additional processing steps, the projected cost of CF SMC for Class A surface components was estimated to be too high for commercial truck applications. Therefore, development of CF SMC for exterior Class A surface quality components was held in abeyance in order to pursue lower-cost, lightweight, low-density, glass-fiber-reinforced SMC for Class A surface components.

Assembly Process Evaluation

Preliminary evaluations of bond strength were made for CF SMC plaques at adhesive bond gaps ranging from 0.5 to 3.0 mm. Lap shear tests run at ambient and elevated temperature show CF SMC bond strengths generally twice those of glass-fiber SMC. The evaluation confirmed that the bond strength decreases as the bond gap increases. Ongoing investigations to provide bond performance data for alternative constructions will be required. The data developed will be used in hood finite-element analysis calculations.

To evaluate the processing characteristics of various combinations of lightweight SMC materials, prototype hoods are being built using the production tooling for an existing hood. The prototype hoods are being fabricated using low-density glass-fiber SMC Class A outer panels and inner reinforcements constructed of glass- or CF-reinforced SMC. The prototype hoods will be used to assess manufacturing process variability, dimensional stability, and adhesive bonding characteristics. To evaluate the viability of the lightweight materials in the production environment, the hoods will be run through the normal assembly plant production processes and evaluated for surface quality, paint quality, and bond read-through.

Cost and Weight Evaluation

Initial concept work has concluded that a 40% to 60% weight reduction is within range, as samples in the required reduced material thickness have been successfully molded. Preliminary cost estimates of the CF SMC hood indicated a higher-than-expected cost premium based on the current best estimate of CF SMC material costs. Because CF costs have risen recently as a result of increased world demand and insufficient supply capacity, alternative constructions are under review to reduce CF-reinforced truck hood costs. At this time, it is anticipated that CF production capacity will increase. However, it is difficult to predict whether world demand will also increase and thereby keep CF material costs high. To build a business case for a lightweight CF SMC truck hood, CF material costs must come down and a stable supply must be ensured.

Conclusions

The project has made good progress in finding promising materials and developing processes. The early work is very encouraging because material properties for structural applications are generally on target. Molding processes similar to those for current glass-fiber SMC can be used for structural applications. Assembly bonding processes appear to follow those of glass-fiber SMCs, with significantly increased bond strength. Most of the potential weight reduction has been achieved. CF SMC material costs for components requiring Class A surface quality are projected to be too high for

commercial vehicle applications. Alternative constructions appear to present a more reasonable cost/weight value.

E. Advanced Composite Support Structures

Principal Investigator: Brian Knouff, PhD

National Composite Center.

2000 Composite Drive

Kettering, OH 45420

(937) 297-9458; fax (937) 297-9440; e-mail: bknouff@compositecenter.org

Project Manager: Jay Batten

Delphi Corp.

3900 Holland Rd

Saginaw, MI 48601-9494

(989) 757-3895; fax (989) 757-42950; e-mail: jay.batten@delphi.com

ORNL Project Manager: Cliff Eberle

(865) 574-0302; fax: (865) 574-8257; e-mail: eberlecc@ornl.gov

DOE Technology Development Area Specialist: Sidney Diamond

(202) 586-8032; fax: (202) 586-1600; e-mail: sid.diamond@ee.doe.gov

ORNL Field Technical Manager: Philip S. Sklad

(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

Contractor: Oak Ridge National Laboratory

Delphi/ORNL Contract No.: 4000021806

Objective

- Lead the rapid implementation of lightweight composite materials in Class 7/Class 8 vehicles via the development of advanced composite support structures, specifically chassis lateral braces, which can number up to six per vehicle. Mass reductions are targeted for 50%.

Approach

- Model composite support structures using progressive failure analysis (PFA) software and finite element analysis (FEA).
- Fabricate prototypes of designed structures.
- Mold composite test plaques to be used in the task on "Attachment Techniques for Heavy Truck Composite Chassis Members." The data from those tests will be integrated into our design models.
- Analyze materials characteristics of the test plaques such as fracture toughness and fatigue life.

Accomplishments

Modeling

- Used PFA software to provide a means of modeling damage and failure in composites, accurately predict the number of cycles to failure as a function of void fraction, and predict the elastic constants.
- Designed all carbon and all glass composite lateral braces using six load cases.
- Optimized the geometry by transforming the current U-channel into a box beam and integrating the end brackets into the center piece.

- Demonstrated weight savings of 70%.
- Fed results in the design iterations back to the Joining Team, which then requested that plaques be molded for various tests.
- Displayed the second all-composite prototype model at the ACSS Program Review and 2nd value analysis/value engineering meeting (VAVE) on August 10, 2004.
- Fabricated several different composite test panels to support both the joining and modeling database programs.
- Discovered that the void content had a dramatic effect on fatigue life and that the plaques were not reaching their ultimate T_g (glass transition temperature) without a postcure.
- Conducted Mode I fracture toughness studies and fabricated Mode II fracture toughness fixtures.

Future Direction

- Complete design validation for this application and then pursue a new application. Associated with this program will be a higher-level effort in composite-to-composite joint design with the added variable of hole placement.

Introduction

The purpose of this effort is to lead the rapid implementation of lightweight composite materials in Class 7/Class 8 vehicles via the development of advanced composite support structures. This task specifically addresses lateral braces; primary beams are being targeted for future work. The mass reduction target is 50%. The benefits of mass reduction in commercial vehicle applications are well known. They include increased fuel economy and a larger payload, which translate into fewer total trips and thus fewer vehicles on the road. This leads to less traffic, which aids highway safety, and decreased emissions. Support structures offer an opportunity for significant weight savings. However, this area of the vehicle also represents a large hurdle in terms of composite applications and market acceptance.

The application of focus is a Class 8 tractor lateral brace (Figure 1). The estimated total annual usage of Class 8 lateral braces could exceed 1 million by 2007. At a current typical weight of 9 kg for Class 8 tractors, weight savings would be 4.5 kg per part. With up to six braces per vehicle, the resulting total weight savings would be 27 kg per Class 8 tractor.

To facilitate this work and future endeavors, advanced FEA and PFA software is being employed and developed. The FEA software contains a unique

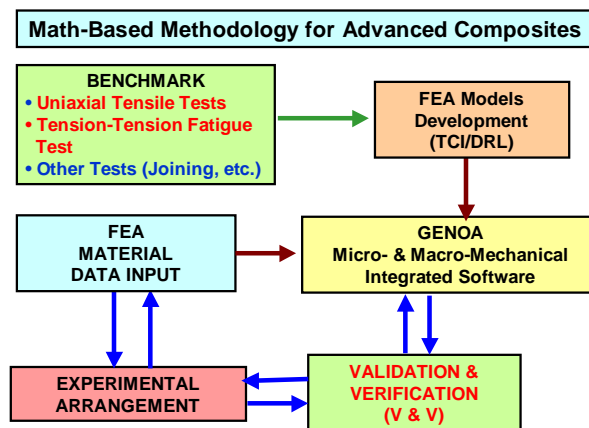


Figure 1. Schematic showing logical synergism between PFA, FEA, and experimental data.

optimization algorithm that allows for the rapid optimization of such design variables as part thickness, fiber angle, fiber type, and even part shape while minimizing mass, strain, or even cost.

PFA, although in development for composites, will provide the ability to model composite behavior in durability and fatigue situations—unlike any other software our team has examined or is aware of.

Modeling

The modeling effort was separated into two parts:

1. PFA
2. Prototype design with FEA

PFA was used to satisfy the following requirements:

- Generate required material database for micro- and macro-mechanical simulation of fracture and fatigue of composite joining systems.
- Develop predictive models of composite joint failure based upon failure mechanics theories.

Figure 1 shows the relationship between physical testing, FEA, and PFA used to develop the math-based methodology for advanced composites. The physical testing of the composites in both static and fatigue supplied the database to model these conditions. In this case, the material was a 3-dimensional (3D) fabric reinforcing a vinyl ester thermoset. An S/N curve of the neat resin matrix was produced (Figure 2). It was required to model the resin behavior for complex geometries, such as the 3D composite material employed.

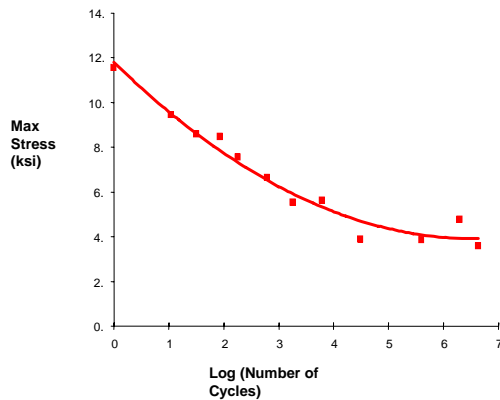


Figure 2. S/N curve for neat resin polyurethane modified vinyl ester system.

Initial results have been promising. PFA has been able to accurately represent the Poisson ratios as well as longitudinal and transverse elastic moduli. An attempt was also made to determine a “Miner’s Rule” for composites, but that has been determined to be somewhat complex and requires further investigation.

The main accomplishment to date is the ability to model the effect of void content on fatigue behavior in the test plaques. Figure 3 shows experimental data with symbols and predictions with

lines. For 13% and 10% void content, the prediction line fell within the scatter from the data. For 2% void content, it actually coincided with the data. This is a major breakthrough, as a void content of 10 to 13% has been shown to decrease fatigue life by a factor of 40 compared with a void content of 2%. This phenomenon has now been not only documented but also modeled and predicted. Without this capability, predictive modeling would have to be generated from empirical correlations.

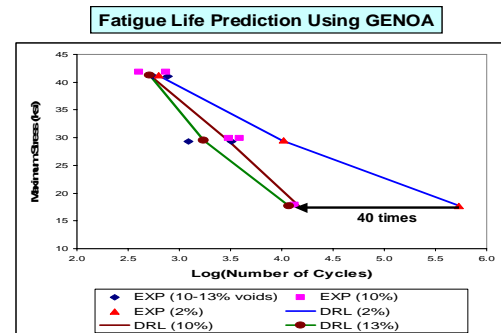


Figure 3. Good correlation between PFA (lines) and data (symbols) for S/N curves at different void concentrations.

Prototype Design with FEA

Actual design requirements of the application lateral brace were not available from the customer. However, the current steel design was in IGES format. This file was imported and meshed for FEA.

No design requirements were associated with this application. In other words, the customer did not know what load levels the part would experience in its life nor how stiff it had to be to perform properly. This is not unusual in the Class 8 truck market. Steel with a thickness of 0.25 in. is an industry standard, and it has been shown to perform well in chassis applications. The customer supplied IGES files of both the center steel brace (stamped) and the cast end brackets.

Each part will experience six basic load cases:

- **Axial extension:** a tensile or compressive load along the length of the brace, perpendicular to the primary beams. This load case will occur during lane changes and cornering, for example.
- **Racking:** an applied load on the brace flanges parallel to the primary beams. It can also occur during cornering and braking, as one side of the chassis lags briefly behind the other.

- **Rolling:** a result of one wheel being elevated above the other on the same axle. Potholes or road debris will cause rolling, which is a force perpendicular to the road surface.
- **Torsion:** a twisting motion that can also occur during a pothole or debris hit. One side of the chassis lifts and pivots to accompany the terrain, resulting in a twisting of the lateral brace.
- **In-plane bending:** a movement applied on one side of the flange around the primary beam. It can occur when one side lifts or when the chassis experiences a jarring motion from rough terrain.
- **Out-of-plane bending:** one primary beam trying to circle the other. Sharp turns can cause this load case to be applied.

The center steel section was first meshed and modeled in FEA. The constraints and loads were applied evenly along the ends. Using the exact same mesh, composite properties were applied to the model and FEA optimized the design variables to satisfy the stiffness requirement. Specifically, the design variables were the thickness and fiber angles of each of eight plies, the single point constraints were all nodes at one end constrained in all six degrees of freedom, the load case was 2000 N-mm at the other end, the design constraint was a maximum deflection of 1.2 mm, and the design objective was the minimization of mass.

The optimization resulted in a lay-up of three stacks of $[0_2/90/23_6/-23_6]_s$ of prepreg with each ply 0.15 mm thick. The total thickness of the part was 13.5 mm and the part weighed 5.3 kg, resulting in a mass savings of 58%.

After this design, a meeting with the customer was held to determine what other options were available. It was determined that the holes were not needed in the center section. Additionally, it was discovered that torsional rigidity was further improved by adding a fourth wall to the bottom, thereby making the brace a box beam.

To minimize assembly time, the design was further optimized by combining the end brackets with the centerpiece. The material was changed from carbon prepreg to 3D carbon fabric to reduce the material cost. A topology was then performed to

determine the areas of most required mass, or stiffness. Figure 4 represents the thick areas with the darker gray areas that make an 'X' shape on both sides of the part. Also, notice the darker areas calling for reinforcement of ends on top and bottom. Using the topology results, the part was then divided into finite elements parts with each part optimized for thickness. The result was an end thicknesses of 5 mm with 1-mm thicknesses for the rest of the part.

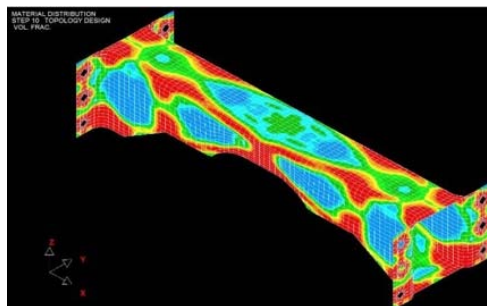


Figure 4. Topology shows areas of high profile (thickness) to accommodate higher-stress regions.

Up to this point, only the torsional load case was considered because of our impression that it was the worst-case scenario. However, with the optimization to a box beam, that was shown to no longer be the case.

Therefore, the additional five load cases were also used for design optimization. All six load cases are shown in Table 1. In the general coordinate system, the X-axis runs longitudinally through the lateral brace itself, the Y-axis is parallel to the primary beams, and the Z-axis is perpendicular to the ground.

For the design of the composite part, the steel lateral brace was loaded until 90% of yield stress failure in each load case. This load then was applied to the composite, which was designed with a safety factor of 2 using Tsai-Wu failure criteria. Table 1 shows the resulting loads used for each case and the corresponding reaction (deflection) of the steel brace.

Table 1. Loads calculated in FEA analysis on steel section to achieve 90% von Mises yield stress. The deflection is also shown.

Load case	Load (kN) (kN-mm)	Max VM (MPa)	DOF	Deflection (mm)
1. Axial	28.08	527.40	F_x	6.32
2. Racking	8.00	527.34	F_y	52.7
3. Roll	8.86	526.90	F_z	12.6
4. Torsion	1003.42	527.11	M_x	40.8
5. In-plane bending	3882.45	525.00	M_y	2.76
6. Out-of-plane bending	1045.29	527.39	M_z	17.7

It was also determined that the brace could be processed much more easily (with less cost and increased yield) by removing the scallop on the underside and making the box beam straighter. In this design, a 7-mm backing plate was also added to represent the attachment to the primary beam. Topology and part optimization was used again to design this iteration. This iteration was used for the prototyping. Figure 5 shows the model after it was optimized for manufacturability.

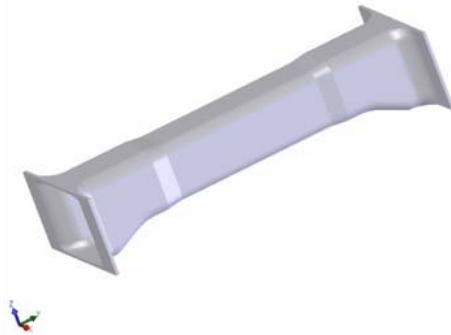


Figure 5. Optimized geometry smoothed and drafted for manufacturability.

Further investigation took place to optimize the design. Two hybrid designs of steel and glass were investigated first. Both of these hybrid concepts use traditional joining methods because of the steel endplates and offer a potential low-cost alternative.

Five different all-glass composite designs were also considered. The flanges of the endplates are reinforced by geometric hollow ribs in the first concept, whereas these ribs are replaced with an expanding tube at the end in the second. The third concept attempts to decrease the middle section geometry from the previous design. A more radical conceptual design is offered in the fourth: Ribs are

placed longitudinally along the tube, thereby also serving as the attachment flanges. This can be accomplished process-wise by employing foam inserts that remain in the part or using metal inserts that disassemble. The fifth concept uses flat attachment plates instead of the rib design in all four corners of the tube. The novelty of this analysis is that the lateral braces were attached to sections of the primary beams, to which the loads were applied.

Each of the designs has been compared in all six load cases in terms of displacements. These six load cases are

1. Axial extension in the X direction (11-X)
2. Racking in the Y direction (12-Y)
3. Rolling in the Z direction (13-Z)
4. Torsion around the tube (14-MXX)
5. In-plane bending (15-MYY)
6. Out-of-plane bending (16-MZZ)

Table 2 lists the load cases as well as the normalized deflection of each design, with the steel base case having a deflection of 100%. A percentage less than 100% means the composite design was stiffer. Alternatively, a value higher than 100% means it is less stiff, or deflects more as a result of similar applied loads.

In the extensional load case, the hybrid designs were slightly stiffer than the base case. However, each one of the glass designs showed stiffness decreases. The hybrid designs also showed stiffness increases in the racking loadcase, with only concept 2, of the all glass designs, showing a significant increase in stiffness.

None of the designs fared better in rolling than the base design. However, the hybrids performed the best. Contrary to this fact, all of the concepts were torsionally stiffer than the baseline case. However, the in-plane and out-plane-bending cases showed

Table 2. Comparison of seven designs to baseline in the six load cases

Load case	Baseline	Hybrid-1	Hybrid-2	Concept-1	Concept-2	Concept-3	Concept-4	Concept-5
11-X	0.080	0.072	0.079	0.135	0.101	0.113	0.126	0.180
%	100%	91%	99%	169%	126%	142%	158%	226%
12-Y	2.859	1.132	1.212	3.445	1.882	2.631	3.243	4.255
%	100%	40%	42%	120%	66%	92%	113%	149%
13-Z	1.972	2.113	2.320	4.271	2.697	3.182	5.556	6.353
%	100%	107%	118%	217%	137%	161%	282%	322%
14-MXX	3.243E-02	7.168E-04	6.251E-04	4.392E-03	3.442E-03	5.293E-03	4.579E-03	4.159E-03
%	100%	2%	2%	14%	11%	16%	14%	13%
15-MYY	1.981E-05	3.076E-05	5.834E-05	7.315E-05	2.936E-04	3.902E-05	7.241E-05	1.097E-04
%	100%	155%	295%	369%	1482%	197%	366%	554%
16-MZZ	1.279E-03	1.327E-03	1.402E-03	4.603E-03	2.684E-03	4.052E-03	3.862E-03	5.025E-03
%	100%	104%	110%	360%	210%	317%	302%	393%

there to be a considerable need for redesign in each of the seven concepts.

Prototyping

Figure 5 was used as the design for the prototype model. The resin transfer molding (RTM) process with fiber architecture achieved via a bi-axial braided fabric was chosen to fabricate the prototypes. Table 3 lists this architecture. The braided fabric took the form of several layers of a braided sock that could be threaded over a two-piece mandrel and the assembly loaded into a multi-piece aluminum mold.

The aluminum mold (Figures 6 and 7) consisted of six pieces that encapsulated and located the two-piece mandrel covered with the fiber assembly. The mold was cored to allow temperature control via ancillary thermolators to aid in the curing of the injected matrix. The matrix chosen was a two-component epoxy system with good thermal and environmental properties. The resin was injected at an elevated temperature to lower its viscosity and reduce the infusion time. The mold design incorporated a bleeder system that created minimal flash even though the resin injection pressures exceeded 100 psi. The infusion time was less than 5 minutes; however, the cure-demold time took several hours because of the ramp-up and cool-down thermal requirements for the several hundred pounds of aluminum mold. In addition, the multi-piece mold was assembled and disassembled by hand. Production tools will incorporate much easier

assembly/disassembly and will be water-cooled to allow for rapid cycle times.

The parts weighed 7.7 lb with a targeted fiber volume of 55%. Constant fiber content was maintained in the varying cross-section by placing additional layers of braided sock as needed. Bi-axial braided preforms conform much more easily to the variations in the mandrel geometry as opposed to tri-axial braids. Computer-aided part design and tool manufacturing contributed significantly to a time frame of less than 4 weeks from concept to the part shown in Figure 8.

Molding

The fabrics used for this project were

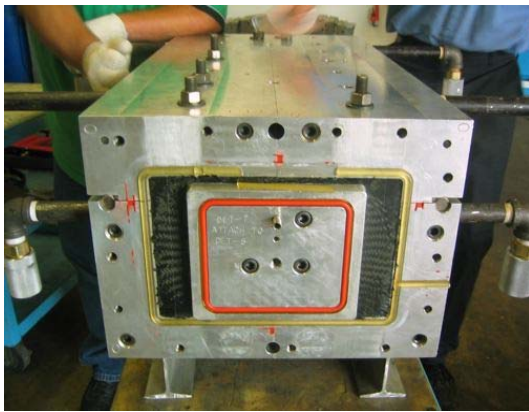
- 3D glass 96 oz/yd²
- 3D carbon 32 oz/yd²
- Stitched glass 0–90° 17.8 oz/yd²
- Plain-weave glass 10.5 oz/yd²
- Unidirectional glass 10 oz/yd²

All panels were molded to a nominal thickness of 0.100 in. To achieve this, the following lay-ups were used:

- 3D glass 96 oz/yd²—1 layer
- 3D carbon 32 oz/yd²—5 layers
- Stitched glass 0–90° 17.8 oz/yd²—5 layers
- Plain-weave glass 10.5 oz/yd²—9 layers
- Unidirectional glass 10 oz/yd²—10 layers

Table 3. Braided fiber architecture used for the prototypes

Braid laminate design for National Composite Center demonstration structure									
	Full-length sleeves			Full-length sleeves			Patch plies		
Product code	Y56L800R			MM26L700R			AP5574		
Box width		4.897	4.897		4.897	4.897	Braid width = 59.2		
Box height		5.358	7.022		5.358	7.022			
Box perimeter		19.179	24.047		19.179	24.047			
Braid condition	Nominal	Use diameter		Nominal	Use diameter		Bias	Warp	Total
Diameter	8.000	6.015	7.65	7.000	6.105	7.65	18.844	18.84	
Angle	45.0	32.7	42.6	45.0	38.1	50.6	60.0	0.0	
Raw Yd/Lb	620	620	620	1800	1800	1800	620	620	
Carrier	272	272	272	500	500	500	336	168	
Ends per carrier	1	1	1	1	1	1	1	2	
Fiber density lb/in. ³	0.065	0.065	0.065	0.092	0.092	0.092	0.065	0.065	
Part fiber volume (%)	51.8%	51.8	51.8	51.8	51.8	51.8	51.8	51.8	
Outputs									
One layer thickness	0.0204	0.0224	0.0204	0.0104	0.0107	0.0106	0.0151	0.0076	0.0227
Number of layers	3			1					??
Local laminate thickness		0.0780	0.0719						0.2039
Overall fiber volume in patch area for an overall laminate thickness of 0.275 in.							52.0%		
Percent coverage (%)	58.5	63.0					45.9		
Oz per yd ²	14.2	15.6	14.3	10.3	10.6	10.5	10.5	5.3	15.8
Ft/lb	4.84	5.76	5.04	7.64	8.50	6.85	2.77	5.54	1.85
ppi	5.4	4.5	5.2	11.4	10.2	12.7	4.9	0.0	
Mtl. reqd. for 3 performs (lb)	6.1			1.4			17.1		

**Figure 6.** Four corners plus two mandrels (ends have been removed).

Two resins were used for the matrix, a polyurethane/vinyl ester blend and a polyurethane modified vinyl ester.

The process chosen to consolidate the constituents was vacuum infusion. Some of the fabric/resin combinations were not infusible. Although the blend of polyurethane and vinyl ester allowed for some gel time extension by changing the chemistry (catalyst, accelerator, and promoter

**Figure 7.** Both top corners removed.

concentrations), the ceiling was found to be between 24 and 30 minutes.

The other resin used in this project was a vinyl ester resin base. This resin showed better infusion properties. The gel time for this resin was extended from 8 minutes (first iteration) to 50 minutes (third iteration), making this resin more infusible. A consistent pattern of bubbles or voids occurred at the intersection of the fiber tows when infusing this resin into a 3D glass 96-oz fabric.



Figure 8. Second prototype part.

This project helped to shed light on the mechanisms of infusion and the importance of fabric orientation. It was noticed that orienting the fiber parallel to the infusion line produced a slower infusion than orienting the main fiber perpendicular to the infusion line. In one case, when the 3D glass 96-oz fabric was oriented parallel to the infusion line, the total infusion time was 20 minutes; but when the main fiber was oriented perpendicular to the infusion line, the infusion time was only 4 minutes.

A second important point for infusion is the effect of changing the layup schedule. For this trial, the stitched 17.8-oz fabric was used with five layers per panel. Two sequences were used: Panel A: $[0-90^\circ, 0-90^\circ]_{2s}$ and Panel B: $[0-90^\circ, 90-0^\circ]_{2s}$.

Panel A infused faster than panel B. The reason is that in panel A, the infusion speed tended to be constant; meanwhile, in panel B, the fiber perpendicular to the resin line (0° direction) flowed faster than the fibers parallel to the infusion line (90° direction), which flowed at half the speed of the zero fiber orientation. In panel A, the resin that flowed along the 0° fibers also was able to transfer to the 90° fibers on both sides. However, in Panel B, a 'dead' zone was created between each of the two 90° layers and resin infusion was impeded.

Material Characterization

Molding

It was found that the initial composite specimens made were performing unacceptably in fatigue. This was found to be the result of having too much clay in the formulation, incomplete cure, and high void content. The elimination of clay in the formulation was easily accomplished, and a post-cure schedule was added to each panel to ensure completion of the polymerization. The thrust of this investigation was the cause and elimination of voids. Voids are detrimental to fatigue properties of composites.

By degassing the resin before infusion and using vertical infusion, the void content was successfully minimized. Figure 9 shows a comparison between an initial plaque (10 to 13% voids) and one of the latest plaques (2% voids).

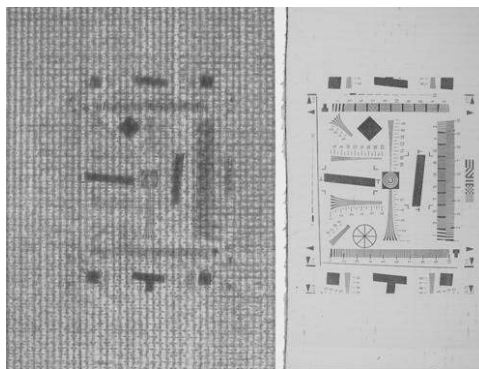


Figure 9. Side-by-side comparison of 10% void plaque and 2% void plaque.

It was necessary to generate and test neat resin samples for input into the PFA database. The resins were characterized under a dynamic mechanical analyzer. This unit, used to measure the glass transition temperature, showed that all the samples needed a post-cure to obtain a saturated cross-link density.

Fracture Toughness

Another method of obtaining material data to support PFA was the use of fracture mechanics. Mode I fracture toughness testing initially gave mixed results, but the testing technique has now been improved. A fixture for Mode II has been fabricated.

The results include an interesting observation of the stitched or z-fibers in the 3D fiber architecture. The fibers not only prevent catastrophic crack growth but also actually impede it to the point of rerouting the crack through the thickness of the specimen. Possibly, the fracture toughness could be increased by decreasing the proportion of z fibers.

Testing with the neat resin showed a continuous fracture toughness (~ 590 J/m) regardless of crack length, thereby providing a noncatastrophic Mode I failure.

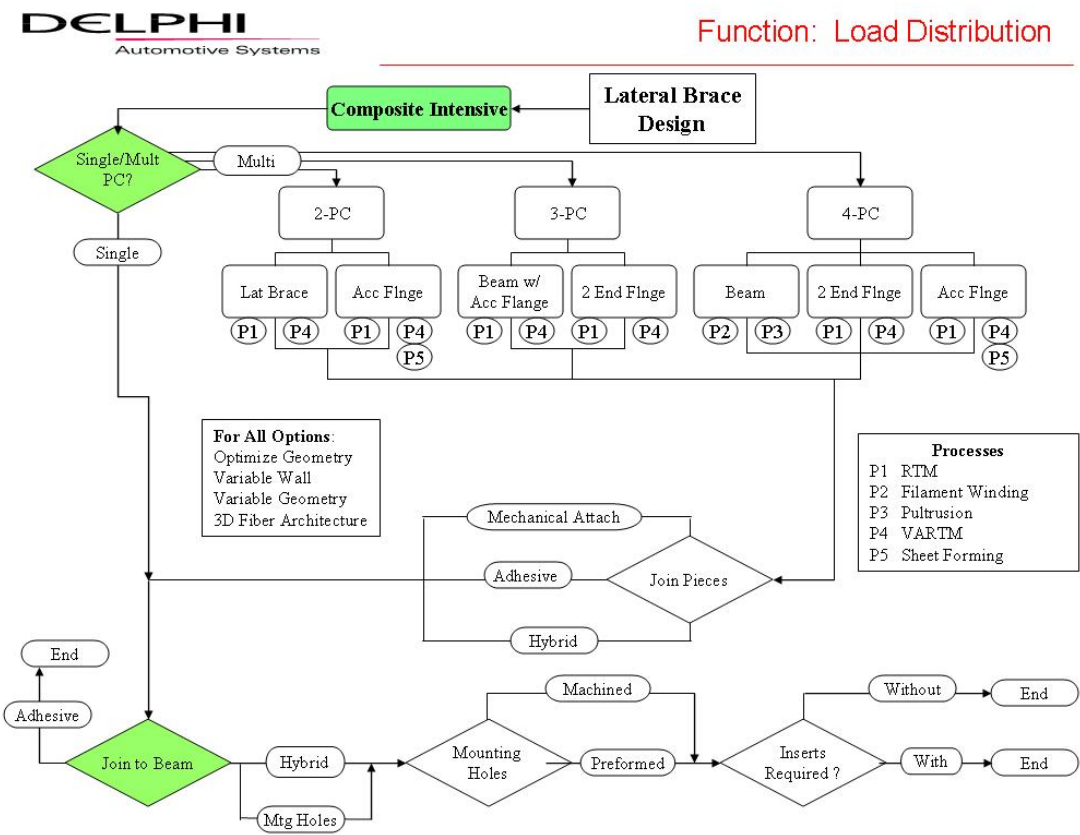
Conclusions

Accomplishments in FY 2004 include the following:

- Integrated PFA to help design composite parts in durability and fatigue environments.
- Successfully predicted S/N curves of composite plaques with varied levels of void content.
- Successfully predicted elastic constants of 3D fabric composites.
- Brought an optimized design close to completion on the lateral brace using 3D fabrics. FEA was used to generate the designs.
- Achieved weight savings of more than 50%.
- Integrated a cost model into the optimization program.
- Considered all-carbon, all-glass, and hybrid materials.
- Successfully designed a manufacturable prototype.
- Successfully fabricated a prototype using aluminum tooling and displayed it at the August VAVE workshop. Design to fabrication took 4 weeks.
- Determined that the aluminum tool can fabricate up to 500 parts.
- Employed both vacuum infusion and RTM to mold plaques for the process development (elimination of voids) and fatigue and durability testing for input into the PFA database, and for the “Attachment Techniques for Heavy Truck Composite Chassis Members” project.
- Successfully measured the mode I fracture toughness for the 3D fabric. It has been determined that the frequency and placement of the ‘z’ fibers can have a major effect on this value.

Future Direction

Results from the VAVE workshop produced the functional analysis system technique model shown in the following chart. The chart envelopes several paths for the design, processing, and attachment of the lateral braces in the tractor suspension. Once design validation is successful, a new application will be pursued.



F. Hybrid Composite Materials for Weight-Critical Structures

Principal Investigator: Mark T. Smith

Pacific Northwest National Laboratory

P.O. Box 999 Richland, Washington 99352

(509) 375-4478; fax: (509) 375-4448; e-mail: mark.smith@pnl.gov

Principal Investigator: Bill Roberts

PACCAR Technical Center

12479 Farm to Market Road, Mount Vernon, Washington 98273

(360) 757-5286; fax: (360) 757-5370; e-mail: broberts@paccar.com

Technology Development Area Specialist: Sidney Diamond

(202) 586-8032; fax: (202) 586-1600; e-mail: sid.diamond@ee.doe.gov

Field Technical Manager: Philip S. Sklad

(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

Contractor: Pacific Northwest National Laboratory

Contract No.: DE-AC06-76RLO1830

Objective

- Develop and demonstrate (1) the application of hybrid composites and composite/metal hybrids to heavy-duty vehicles and (2) the capability to integrate these materials choices into moderate-volume production.
 - Develop and demonstrate the potential for major weight savings (>50% on a component basis) in critical structures applicable to truck cabs and support components.
 - Demonstrate the basis for use of hybrid metal-composite systems to reduce weight via proof-of-principle experimentation.

Approach

- Investigate the potential of new materials and manufacturing technologies to effect major weight reductions for heavy-duty vehicles.
- Assist in demonstrating the applicability of composites and composite/metal hybrids to operational vehicles with little or no cost impact.
- Provide the experience base to develop the design and analysis tools, as well as the scientific understanding of the factors affecting molding and materials performance.
- Provide the materials suppliers with a market that can stimulate demand, leading to an increase in their production capacity. This will help reduce materials costs by creating higher volumes.

Accomplishments

- Completed three sets of prototype hybrid door components, which were delivered to Pacific Northwest National Laboratory (PNNL) by the subcontractors. The key components include sand cast magnesium door inners (Style and Tech) and molded hybrid glass/carbon fiber upper door frames (Profile Composites).
- Initiated door hardware fitting and assembly tasks at PACCAR and PNNL. These include dimensional inspection and fitting of the magnesium lowers to the hybrid composite uppers, as well as initiation of material adhesive bonding tests at the PACCAR Tech Center.

- Completed bonding adhesion testing of composite and metal systems at PACCAR Tech Center and demonstrated excellent bond strengths and desired bond failure behavior.
- Received fitted hardware at the PACCAR Tech Center for final prototype assembly and bonding. Assembled prototype doors will be placed in the PACCAR cab shaker test system for simulated durability testing. The assembly and testing milestone has been delayed until early 2005 in order to successfully complete bonding adhesion development tests.

Future Direction

- Assemble three prototype hybrid material doors for testing by PACCAR. Plans call for cab shaker tests to be conducted in the first half of 2005.
 - Based on component design and assembly tasks, update door manufacturing cost models for PACCAR (PNNL and Mercia).
 - Compile a final report at the conclusion of the prototype demonstration phase.
-

Introduction

Current materials and manufacturing technologies used for heavy vehicle door systems are often dictated by the high cost of tooling and the relatively low production volumes for Class 8 trucks. Automotive-style stamped door designs, whether of steel or aluminum, require multistage stamping dies that are generally cost-prohibitive at lower production volumes (<50,000 units per year). Alternate materials, such as glass-reinforced sheet molding compound (SMC), require less expensive tooling and can provide a Class A finish; but the relatively poor specific properties of SMC tend to compromise design and result in a heavier door system. For many production truck cabs, a simple aluminum extrusion frame is used with a flat aluminum sheet riveted to the frame. Although this approach does not require expensive tooling, the use of constant cross-section extrusions in the frame is less than optimum, and it requires more assembly labor than other approaches. PACCAR, a world leader in Class 8 truck design and manufacturing, teamed with PNNL to explore alternate “hybrid” door system designs that minimize tooling cost and per/part door cost, while providing a lightweight, structurally stiff, automotive-style door.

Project Approach

The initial approach to development of the hybrid door system was to perform a structural analysis of an existing PACCAR door design and determine what the design and performance goals should be for new-generation door systems.

PACCAR provided a number of weight, cost, and performance parameters that it considered important for future door designs. PNNL was tasked to survey existing and emerging materials and manufacturing approaches that could be applied to a new door design. Following completion of this survey and analysis of existing door designs, PNNL, with design assistance from Mercia, Ltd., developed a series of five door design concepts that included combinations of large die castings, extrusions, carbon- and glass-reinforced composites, and conventional SMC and stamped aluminum exterior panels.

Following a concept review meeting with PACCAR, an optimized hybrid door design concept was selected. The door concept was then defined using computer-aided-design tools and analyzed with finite element models to validate performance, weight, and cost. After determining that the prototype design met or exceeded all performance and projected cost targets, PNNL and PACCAR selected methods to produce prototype components for the full-scale assembly and testing phase of the project. The finite element model of the prototype door system is shown in Figure 1.

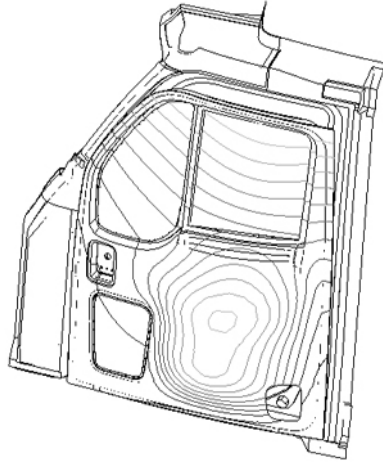


Figure 1. Finite element model of prototype door system under simulated loading conditions.

Conclusions

The prototype development of hybrid materials components for an advanced heavy truck door was completed by the team and its selected subcontractors. Initial prototype assembly has been initiated by the team, including inspection and assembly fitting, as well as adhesive bonding development. Three prototype doors will be assembled by the team for cab testing and evaluation during the first half of 2005. The hybrid door design that will be prototype-tested reduces door weight by 37%. If the hybrid design were to move into production, the use of a stamped aluminum outer panel (cost-prohibitive during the prototype stage) would improve structural performance, reduce cost to project goals, and increase weight savings to 55%.

G. Application of Carbon Fiber for Large Structural Components

Principal Investigator: Kevin L. Simmons

Pacific Northwest National Laboratory

P.O. Box 999, MSIN: K2-44, Richland, WA 99352

(509) 375-3651; fax: (509) 375-2186; e-mail: kl.simmons@pnl.gov

Technology Development Area Specialist: Sidney Diamond

(202) 586-8032; fax: (202) 586-1600; e-mail: sid.diamond@ee.doe.gov

Field Technical Manager: Philip S. Sklad

(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

Contractor: Pacific Northwest National Laboratory

Contract No.: DE-AC06-76RLO1830

Objective

- Develop selective reinforcement technology that can be applied to large cab components to improve specific stiffness and strength, while reducing overall component weight.

Approach

- Determine the capability of low-cost carbon fibers to be hybridized with glass fibers to provide substantial weight and cost reductions in large cab components.
- Develop a system for preforming carbon and glass fibers together that will allow components to take maximum advantage of the capabilities of selective reinforcement alignment and property contribution.
- Develop models for the analysis of hybrid chopped-fiber preforms and composites that allow the thermal and structural properties to be developed and compared with experimental analysis.
- Perform structural testing to define the limits of the applicability of the carbon/glass hybrid reinforcement materials to the large structures and develop guidelines for applications that may be used by original equipment manufacturers (OEMs).
- Design and develop critical subsection components of large structures to use in correlation with the predictive models and to validate the structural application criteria. Determine the capability of the materials to be fabricated in full-scale components and determine the performance of these full-scale components in real application scenarios.

Accomplishments

- Developed the first Class A structural carbon composite panels for truck applications.
- Showed impact performance that is 2–3 times higher than performance values of standard structural composites.
- Developed hybrid carbon composite with improved impact performance over fiberglass composites.
- Demonstrated thin (2.5 mm) panel fabrication and resin transfer molding capability.
- Demonstrated panel molding with varying cross-sections from 2.5 to 7 mm in a single component.
- Performed panel molding with various filler types and loading, and selected optimum fillers for achieving Class A surface.

- Performed mechanical and impact tests on a range of panels.
- Developed and performed process trials with a new tooling system that allowed the system to work together, including improving thermodynamic control necessary for achieving mechanical and impact properties.

Future Direction

- Scale up to test a production component selected by the cooperative research and development agreement (CRADA) partner.
 - Optimize the resin system using different fillers.
 - Test and validate thickness constraints on panels to achieve structural performance on surface-coated thin hybrid panels.
 - Fabricate test tooling for production-level component.
 - Test and validate barrier coat and optimize for surface profile.
 - Verify tooling performance and long-term viability.
-

Introduction

Selective reinforcements with stiffer fibers have the potential to reduce both costs and weight simultaneously even at current price points. Their introduction is hindered by a lack of understanding of the fibers in existing processes and the need to develop robust methods of preforming glass and carbon fiber materials together. In addition, the capability to attain Class A surface finish is required; and potential development of bonding agents and the ability to model thermal and structural performance of the materials in a hybrid system are needed. The recent development of composite systems combining carbon fiber reinforcement with low-cost automotive and marine resin systems provides the opportunity for selective reinforcement of a broad range of structural composite components.

The purpose of this project is to develop the design and materials processing technology that will facilitate the application of low-cost hybrid glass fiber and carbon fiber reinforcements in large composite components, resulting in reduced weight and improved structural performance. This project will also seek to advance low-cost carbon fiber materials developed by industry by advancing the introduction of low-cost resin systems that are compatible with current heavy vehicle structural composites.

Fiber Preform Development and Evaluation

The requirement for a discontinuous fiber preform that can accommodate multiple project objectives was a key issue in the project. Critical aspects included allowable loft and compressibility, capability to achieve Class A surface, ease of fiber placement, ability to tailor for placement of local additional carbon fiber reinforcement, minimum processing cost, and repeatability of processing. The approach calls for a given amount of loft to be available but for both compressibility and the capability to provide a high-permeability resin flow path. The method and application of the surface fibers have provided benefits in tailoring fiber content and have assisted in achieving success in the Class A arena.

To supply the various molding trial requirements, different core densities and fiber surface densities were evaluated. Packing levels were from net to 60% compaction, which varied fiber loading in the composite from effective values of 25% to well over 45%. Fiber loading in the carbon fraction was approximately 50% and allowed excellent surface density and allowed fabrication of a thin, high-stiffness panel. This is clearly seen in the test results for flexural properties versus the results for tensile properties. Figure 1 shows the surface available from the sample panel.



Figure 1. Molded preform indicating discontinuous fiber surface.

Hybrid Resin Evaluation

The development effort has remained focused on using a carbon- and fiberglass-compatible resin system. This has proved to be a valid selection based on impact test data that indicate excellent performance with carbon fiber systems as well as glass and other systems (Figure 2). The resin is tailored for use in a resin transfer molding (RTM) process. Several features of the development project have been mentioned by the resin supplier as being unique and beneficial based on the project. The capabilities to develop a truck-quality Class A surface without low-profile additives (which compromise toughness) and to achieve consistent molding are both new to the industry. The excellent toughness seen in carbon hybrid composites is also an industry first, described with enthusiasm by the resin supplier as “ballistic performance.” One significant issue with carbon composites is their lack of toughness and brittle failure nature. The team had concerns about the minimum achievable panel thickness because of this issue. Limiting panel thickness would have severely hindered capability to be cost-competitive and provide the weight savings desirable. Resin and process evaluation indicated a need for a system with close temperature control, which required development of tight tolerances on the process and equipment.

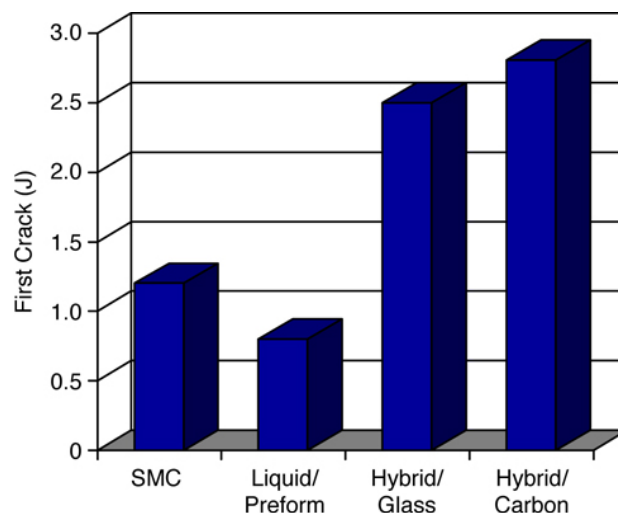


Figure 2. Resin system allowing excellent impact energy.

Molding Trials

Molding trials have consisted of flat panels and large test tool molding trials. Flat plaques were made primarily at Pacific Northwest National Laboratory to develop and verify resin and additive processing conditions as well as to determine the flow rates achievable through preforms of different thicknesses and compaction. Full-scale test tools (approximately 3 × 5 ft mold) were fabricated (Figure 1) to translate these results into a size and form that could demonstrate the effects of different geometries, fiber loadings, and resin flow paths. Experimental results for each provided a process map for the CRADA partner’s confidence in molding actual on-vehicle test components to be provided later this fiscal year. Local condition variability was a key issue in the process control and development efforts, especially as the resin rheometry effects varied with time as reactions occurred.

Several different conditions had to be addressed in order to achieve consistent and reproducible moldings. These included density and compressibility of the pre-form, wettability of the surface fibers, surface energy of the mold’s A and B sides (provided by the particular mold releases), flow-rate into the mold and lag between flow front and fiber wetting front, vacuum level, injection pressures, and mold and materials temperatures. Their effects were often interrelated as regards quality of the components produced. Studies were developed to evaluate common mold release agents and to determine the level of “slip” required to

effectively de-mold parts without causing pre-release at the part surface. This surface requirement proved difficult to achieve, since the materials with medium slip would build up on the tooling and degrade the surface finish. High-slip materials almost always resulted in pre-release at the tool surface, resulting in degradation of the Class A finish capability. Systems evaluated included primarily semi-permanent films. A combination of materials was developed to provide excellent release off the B-side tool and limited release off the A-side to achieve the Class A finish required. Testing is continuing with newly developed formulations for decreased buildup and with internal glyceride-based fatty acid release agents. Surface wettability also impacted the molding quality and the surface pin-holes and voids based on wetting of the fibers in direct contact with the surface.

Four different fabric carriers were evaluated to provide control of resin-injection back-pressure and to determine effective properties with different compressibilities. The best surface finishes achieved were provided by materials that had lower-than-desired permeability and restricted resin flow on the thinner areas (2.7–3.5 mm) of the test parts. After analysis of flow rate and injection pressure parametric studies, vendors have been approached to modify their materials for optimum functionality. New materials to achieve both flow rates required at optimum process pressures and required compressibility of the preforms should be available to us in early FY 2005.

Although temperature has a very significant effect on resin viscosity, cure times, and fiber wetting, it was determined in studies that a very limited temperature range was feasible for this system, based on resin off-gassing and void formation, catalyst selection, and flow. To achieve viable system performance, equipment specifically designed for these resin systems will need to be developed. Pump and feed/storage system customization was required for the experimental trials, which was not an optimal solution.

Gel-coats from several different manufacturers were tested for performance against the A-side tool. Although all performed adequately, a clear choice emerged out of the five tested to meet the CRADA partner's guidelines. The partner desired a system that needed no post-molding sanding and one that could be scuffed with Scotch-Brite™ or a similar

material and sent straight to paint. A study of gel-coat thicknesses and optimum application parameters was initiated, but it had to be stopped because of environmental concerns. A new air handling system is being installed to mitigate this problem and to allow completion of the study. This system should be operational by early November 2004.

Experimental Testing

Mechanical and impact tests were performed on the panels, and excellent translation of properties for all fiber systems was noted. In an unusual departure from common practice, the impact performance of the carbon fiber panels was better than that of the glass fiber panels. The somewhat brittle nature of the fibers in failure was suppressed by a combination of materials and design. The improvements seen were dramatic and bode well for the usefulness of ultra-thin panels.

Specimens were machined and finished on diamond tools and tested with combination extensometers. Results and failure modes were consistent with previously reported testing on the hybrid system that had used different resin systems, except that the performance was significantly better and reflected the improved adhesion to both material phases.

Flexural fatigue testing was performed on several sets of data to determine the durability. The CRADA partner suggested that the material must be able to endure at least one million cycles. Figure 3

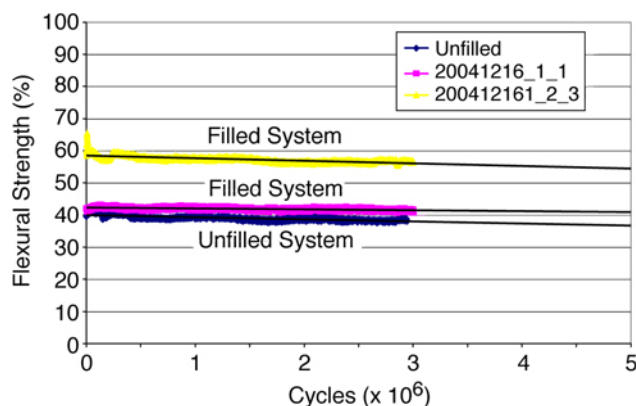


Figure 3. Flexural fatigue comparison at both 40 and 60% of flexural strength. illustrates the fatigue resistance of the developed system at both 40% and 60% of flexural strength. Most specimens were stopped at three million

cycles, but there are data for up to seven million cycles. It was decided to stop the testing at three million cycles so that more samples could be tested.

Fatigue testing on the tooling skin was also conducted to determine the durability of flexing large tooling skins. The material was determined to be suitable, but a more durable surface coating will continue to be investigated.

Rheology measurements were taken on different solids loading of the filler. An optimum range of filler content and particle size was studied and is the basis of future work.

Flow testing under a glass top tooling was accomplished on the four different preform materials. Data showing the different preform materials and the optimized rheology were combined to enhance the understanding of needs and upper limitations.

Cost Analysis

A cost analysis of a large (proprietary) component was performed to determine the break-even points for materials and processes in a typical truck production environment. The effects of a much reduced tooling budget were not factored in because the CRADA partner could not define exactly how and over how many components its internal costing amortized up-front tooling costs.

Tool cost factors would generally sway the costing option in favor of the carbon composite approach. This is because a typical fiberglass injection/compression mold is 4 to 7 times the cost of the RTM tools used in this process. Cost analysis indicated cost parity if carbon fiber is available for approximately \$5/pound and allows for equivalent costing of process ancillaries. The weight savings amounts to 53% over a traditional wet/preform component in production currently.

With tooling cost differentials amortized over two years of production, the break-even point for cost parity is with carbon fiber at just under \$6/pound. Although carbon fiber prices have risen substantially in the past year because of materials shortages, several options for low-cost carbon are being developed. One manufacturer is starting several moth-balled production lines that will ease supply pressures. Aerospace sector supply should increase significantly in 2006 to meet the demand, and these factors will bring pricing back to pre-shortage levels. Long-term pricing for large-volume

orders in FY 2003 was near \$6.10/lb, which is in line with cost parity for this technology given appropriate tool amortization models.

Large Evaluation Tool

In order to evaluate the capability of the process and materials to meet the demands of industry, a proof test component tool was developed. This tool has all the features anticipated in designs, and it was used to evaluate the hybrid process for achieving performance given the requirements of these features. It is not expected that all features can be molded and perform as expected, since the goal of the development is to determine the limitations of the hybrid fiber system as well as provide designers and OEMs with guidelines as to where lightweight materials will be applicable and how to design and manufacture them accordingly.

A new cell was set up for R&D purposes with preforming modifications and resin modification possible in a more appropriate environment. Also, several options for molding were built in that were not possible in the existing production environment but that could easily be implemented once proven. Running this cell, several successful test panel runs were made late in the year using hybrid preforms while meeting requirements of the overall process. Figure 4 illustrates the flexibility of the molding cell and the capability to rotate the position of the mold to change the flow behavior throughout the tool. Samples were provided to be tested early in the next phase. Development of parameters has been much more controllable; and several advanced options for preforming, molding, and materials are being investigated.

A unique proprietary development in a low-cost tooling approach is being used in the test tool. The new technology will be transferred in the scaled-up prototype runs for the client's proprietary component.



Figure 4. Mold cell for test tool setup for large part molding.

Summary

Highlights of progress during FY 2004:

- Molded structural carbon-fiber-based Class A components with a cost-effective hybrid fiber system.
- Achieved significant structural performance in fatigue and impact resistance not previously seen with these composites.
- Achieved molding of very thin section panels and demonstrated weight savings.
- Filed several inventions and potential patents on the process and technology.
- Proved the performance of the tooling approach.
- Demonstrated a system meeting requirements for no sanding prior to paint (all of the partners' current components go through a 100% sanding operation prior to paint.)
- Published results in peer-reviewed compilation and presentation at American Composites Manufacturers Association Annual Meeting.

Conclusions

Initial work has provided some very specific process and product molding parameter goals that

needed to be addressed to make a system with proven capability to move toward commercialization. A series of factors associated with optimizing details of the process technology are being addressed; the CRADA partner is developing an approach to mold full-scale parts that will ultimately go on over-the-road trials. These parts have been chosen to demonstrate the most challenging aspects of the process capability: namely, highly structural, Class A surfaces in direct line-of-sight, with some complex process details required for success. Tooling quotes and negotiations are ongoing, and several aspects of the process are anticipated to go forward for patent protection. Alternative U.S. government applications have been identified that can benefit significantly from this technology. These will be investigated over the coming fiscal year.

Presentations

K. L. Simmons, G. G. Jones, S. P. Walsh, and G. M. Wood, "High-Performance Laminates Using Blended Urethane Resin Chemistry," Composites 2004 Convention and Trade Show, American Composites Manufacturers Association, Tampa, Florida; October 6–8, 2004.

"Application of Carbon Fiber for Large Structural Components," Pacific Northwest National Laboratory On-site Review, April 21, 2004.

Invention Disclosures

"Development of Improved Carbon Fiber Based Hybrid Fiber Structures," IPID 14431-E, submitted May 21, 2004.

"Tooling Method for Application in Rapid Fabrication of Thin-walled Composite Structures," IPID #14430-E, submitted May 21, 2004.

"A Method for Reducing Inter-laminar Stresses in Chopped Fiber Hybrid Composites," IPID #14421-E, submitted May 21, 2004.